"On the Seasonal Variation of Atmospheric Temperature in the British Isles and its Relation to Wind-direction, with a Note on the Effect of Sea Temperature on the Seasonal Variation of Air Temperature." By W. N. SHAW, M.A., F.R.S., Secretary to the Meteorological Council, and R. WALEY COHEN, B.A. Received June 11,—Read June 20, 1901.

The following paper is mainly concerned with the analysis of the seasonal variation of temperature of the British Islands into a series of simple harmonic curves. The variation of temperature is so irregular that the use of this method of analysis for the investigation of the subject may seem to be arbitrary and inappropriate, and a few words of introduction are accordingly necessary to indicate the circumstances under which this mode of dealing with the subject showed itself to be specially adapted for the purpose.

Observations have been made for the Meteorological Office since 1871 with self-recording instruments at the four observatories, Kew, Aberdeen, Falmouth, and Valencia, and the daily means of pressure and temperature from the twenty-four hourly readings of the curves of the barometer and dry-bulb thermometer have been worked out for twenty-five years, but have not yet been published. The means for temperature are represented in Diagram 1 (p. 62), by curves whose co-ordinates are respectively proportional to the number of days since the beginning of the year, and the corresponding twenty-five-year mean of the day's temperature at the several observatories.

The following points may be noticed upon an inspection of the curves:—

(1.) The summer portions of the curves have a larger amplitude and a shorter duration than the winter portions.

(2.) The curves do not exhibit a smooth run, but show a number of irregularities which are, in some instances, particularly in May and December, of considerable magnitude.

Under these circumstances it is difficult to assign any specific number as the normal mean temperature for the particular day to which any actual observed temperature can be referred. To put the same point in other words, it is difficult to say whether a depression between two elevations is to be regarded as a period of abnormally low temperature between two normal periods, or as a period of normal temperature between two abnormally high periods.

It will be noticed that on the diagram smoothed curves have been drawn, which represent with remarkable fidelity the general sweep of the curve, cleared of the irregularities of small period. The smoothed

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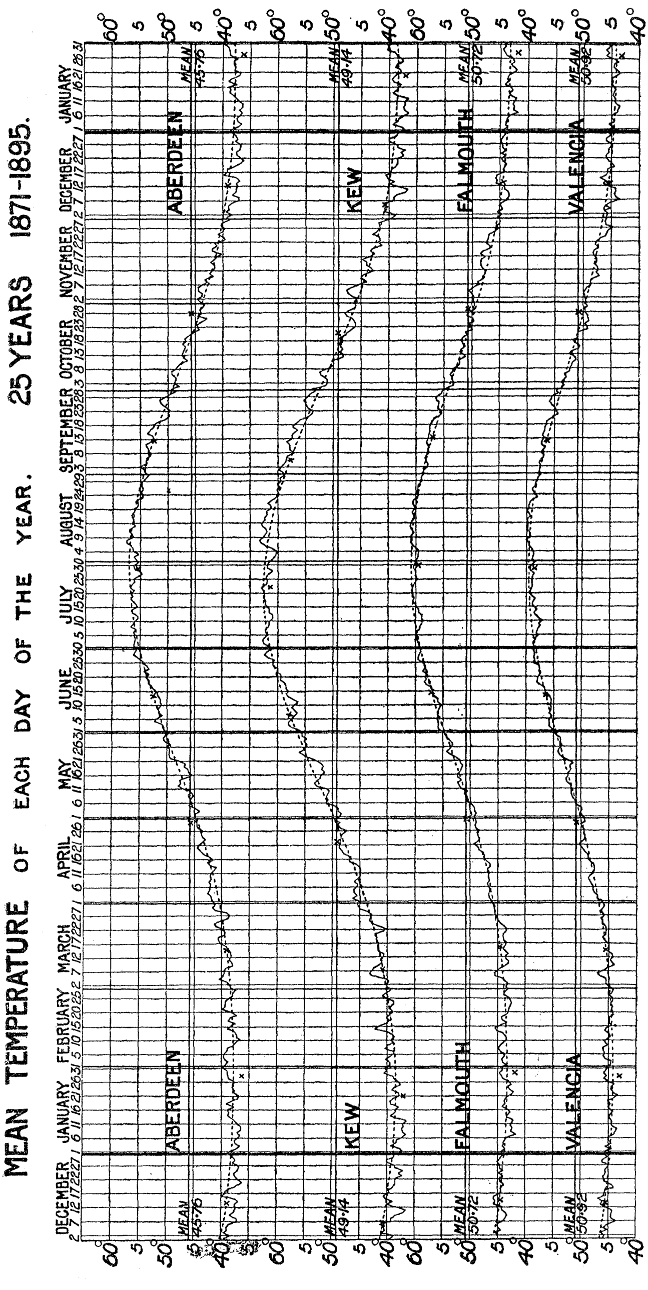
MEAN TEMPERATURE OF EACH DAY OF THE YEAR. 25 YEARS 1871-1895.
DECEMBER
JANUARY
FEBRUARY
MARCH
APRIL
MAY
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER
JANUARY
ABERDEEN
KEW
FALMOUTH
VALENCIA
MEAN 45·76
MEAN 49·14
MEAN 50·72
MEAN 50·92
60°
5
50°
5
40°

Diagram 1.

curves are not drawn by eye merely to smooth out the irregularities, but they have been arrived at by a process of synthesis of simple harmonic curves of the first and second orders.

The irregular lines were first compared with a simple harmonic curve of an annual period, drawn so as to give the same area as the irregular line above and below the line of mean annual temperature, and a general lag of about a month of all the seasons behind the planetary* seasons. The comparison at once disclosed that apart from the irregularities of short period, there was a lag of spring and an acceleration of autumn, and a corresponding exaggeration of the summer maximum and moderation of the winter minimum. This result, which is essentially characteristic of the combination of a second-order sine curve with one of the first order having a maximum at the same epoch, suggested the idea that a normal curve of reference could be formed by combining two such curves.

The first-order sine curve for Kew was accordingly placed so as to make the lag of spring and the acceleration of autumn, as roughly estimated, equal; under these circumstances, the maximum fell on July 23, which coincides satisfactorily with the maximum of the original curve. The second-order sine curve was compounded with this—the period of the second-order curve being six months—and its amplitude† was so arranged as to produce the observed lag of spring and acceleration of autumn; as these had been taken to be equal to each other, the maximum of the second-order curve, and therefore of the compounded curve, corresponded with that of the first-order curve and of the original smoothed curve. A similar process was followed for the other three stations. It is apparent that these new compounded curves give very satisfactory smoothed curves for the whole year for each of the stations. Thus it would appear that the regular periodic variations of mean atmospheric temperature at Kew may be practically represented by the summation of two effects, one of which corresponds with a sine curve having an amplitude of 12°·04 F., and a period of one year, and the other with a sine curve having half the period and an amplitude of 1°·4 F. Similar statements with suitable numerical magnitudes are true of the other stations. These results, which had been reached synthetically, were confirmed analytically within narrow limits,‡ and gave rise to the conclusion that there is in the twenty-five-year temperature curve of each of the British stations, a perfectly regular and recognisable periodic effect, which has positive maxima at the end of January and the end of July, and negative maxima about the end of April and the end of October. It will be seen later on (pp. 65, 66, and 77) that this curious and well-marked effect with a period of six months, having maxima about the end of January and July, is characteristic only of the British Isles, among the places whose temperature statistics have been investigated from that point of view. It is equally conspicuous in the variation of sea temperatures, and is particularly marked in the variation of barometric difference between London and Aberdeen (see Table III, p. 66).

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* The word "planetary" is used in this paper to characterise a variation corresponding to the position of the earth in its orbit.

† The relation between lag and amplitude is as follows: The double amplitude of the second-order curve = annual range × sine of angular lag.

‡ The dotted lines in Diagram 1 show the combination of the synthetic curves of the first and second order; the crosses mark points on the curve of the first order. A comparison with Table I shows that a sensible error was introduced by assuming the maxima of the first- and second-order components to be synchronous in the case of Kew and of Aberdeen.

This paper is devoted to a further discussion of this effect, and an attempt to trace its cause. As the process of harmonic analysis gave results for the twenty-five years which corresponded with the synthetic examination of the curves, it seemed better to deal with the observations in the better recognised and more rigorous way.

Harmonic Analysis of Twenty-five-year Mean Values of Daily Temperatures at Kew.

The mean temperature of any day may be represented by the equation

$$\theta = a_0 + \mathrm{P}_1 \cos (x - \mu_1) + \mathrm{P}_2 \cos 2 (x - \mu_2) + \ldots\ldots,$$

where a_0 is the mean value of the curve for the year, and P_1, P_2 . . . . represent the amplitudes of the first, second, and higher order curves, while μ_1, μ_2 . . . . represent the period of the year, expressed in degrees since the beginning of the year, at which the first maximum of each curve occurs. From this equation, by means of a formula which has been worked out by Sir R. Strachey,* the values of these harmonic co-efficients P_1, P_2, &c., and μ_1, μ_2, &c., have been determined in the Meteorological Office from the twenty-five-year means of the five-day mean temperatures at Kew, Aberdeen, Valencia, and Falmouth. The results of this analysis are shown in Table I. It will be seen that in each case there is a second-order curve whose amplitude is about one-eighth of that of the first-order curve, and that the amplitudes of the curves of a higher order are generally so small as to be negligible, and moreover are very much more variable than the values of the co-efficients of the second-order curve.

Thus it appears that the twenty-five-year mean curve of daily temperature indicates the existence of two effects, represented respectively by a first-order and a second-order curve. The first-order curve represents a primary solar effect, with which we are not here concerned. The purpose of this investigation has been to ascertain the nature and physical cause of the second-order effect.

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* 'Roy. Soc. Proc.,' vol. 42, pp. 61–79.

HARMONIC ANALYSIS OF CURVES.

Table I.—Atmospheric Temperature.

Station.	Period observed.	Mean temp.	Length of summer part.	1st-order curve.		2nd-order curve.			3rd-order curve.		4th-order curve.	
				Amplitude.	Date of max.	Amplitude.	Date of 1st max.	Date of 2nd max.	Amplitude.	Date of max.	Amplitude.	Date of max.
		° F.	days.	° F.		° F.			° F.		° F.	
Valencia....	25 years, 1871 to 1895	50·9	169	7·61	July 29	1·07	Jan. 30	July 31	0·35	Jan. 18	0·07	Mar. 3
Aberdeen ...		45·8	165	9·44	July 28	1·45	Feb. 4	Aug. 5	0·26	Feb. 14	0·12	Jan. 28
Falmouth ..		50·7	167	8·83	Aug. 1	1·18	Jan. 28	July 30	0·15	Feb. 2	0·10	Feb. 23
Kew		49·1	170	12·08	July 23	1·38	Feb. 3	Aug. 4	0·04	Feb. 16	0·12	Feb. 19
„	9 years, '76—'84	49·17	163	11·62	„ 25	1·95	„ 4	„ 5	0·45	Feb. 28	0·32	Mar. 7
„	5 „ '76—'80	48·94	163	11·94	„ 24	2·06	„ 9	„ 10	0·67	Mar. 3	0·30	„ 11
„	4 „ '81—'84	49·17	164	11·10	„ 26	1·84	Jan. 29	July 30	0·22	Jan. 15	0·32	„ 2
„	1 year, 1884	50·52	146	10·99	„ 26	3·57	Feb. 6	Aug. 7	1·08	„ 16	0·61	Jan. 10
„	1 „ 1873	49·3	159	10·95	„ 26	2·83	Jan. 16	July 17	1·38	Apr. 15	1·83	Apr. 3
„	1 „ 1895	49·1	174	14·80	„ 24	1·51	Apr. 22	Oct. 21	2·45	Mar. 23	2·30	Mar. 17
„	1 „ 1898	51·1	176	11·23	Aug. 5	1·38	Jan. 27	July 28	1·50	Jan. 4	0·78	Jan. 31
Oxford	1 year, 1899	50·4	154	12·88	July 12	3·18	Jan. 14	July 15				
Vienna	100 years	49·1	188	19·82	July 18	0·99	Mar. 24	Sept. 24	0·32	Jan. 2	0·41	Feb. 12
Agra	7 years, '68—'74	78·8	198	15·51	June 29	5·22	Apr. 27	Oct. 25	1·14	Feb. 4	0·38	Mar. 11

Table II.—Sea Temperature.

Station.		Period observed.	Mean temp.	Length of summer part.	1st-order curve.		2nd-order curve.			3rd-order curve.		4th-order curve.	
					Ampli-tude.	Date of max.	Ampli-tude.	Date of 1st max.	Date of 2nd max.	Ampli-tude.	Date of max.	Ampli-tude.	Date of max.
			° F.	days.	° F.		° F.			° F.		° F.	
Shetlands	Air	30 years, 1871—1900	—	—	7·55	Aug. 7	1·30	Jan. 29	July 30	0·25	Jan. 13	0·23	Feb. 1
	Sea	3 years, 1880—1882	45	176	7·00	„ 12	0 89	Feb. 11	Aug. 12	0·43	Jan. 11	0·04	Mar. 4
Scilly	Air	30 years, 1871—1900	—	—	8·00	Aug. 7	1·18	Feb. 3	Aug. 4	0·01	Apr. 19	0·09	Feb. 24
	Sea	3 years, 1880—1882	54	176	6·01	„ 10	0·86	„ 10	„ 11	0·19	Apr. 31	0·09	„ 1
Yarmouth	Air	30 years, 1871—1900	—	—	11·96	July 30	1·34	Feb. 13	Aug. 14	0·16	Mar. 5	0·10	Feb. 14
	Sea	3 years, 1880—1882	49	175	10·55	Aug. 13	1·28	„ 21	„ 23	0·03	Mar. 27	0·31	Jan. 6

Table III.—Barometric Gradient (in hundredths of an inch). (Reduced to M.S.L., and 32° F.)

London —Valencia	30 years, 1871 to 1900	—	—	3·07	Jan. 1	1·36	Jan. 15	July 17	0·9	Jan. 15	0·5	Feb. 4
London —Aberdeen		—	—	5·9	Dec. 5	3·4	„ 27	„ 28	0·4	Apr. 19	0·8	Mar. 21

The Effect of the Types of Weather (Cyclonic or Anticyclonic) on Temperature during the Five Years 1876–1880.

The period from 1876 to 1880 was first examined. With the object of classifying the days of this period, the atmospheric conditions prevailing on each day were recorded on a separate card, to be subsequently grouped in any manner that might be thought desirable. The conditions recorded were—

1. The mean temperature.
2. The direction of the wind.
3. The weather.
4. The direction of the gradient (high to low), and
5. The type of the weather prevailing (cyclonic or anticyclonic).

For this purpose weather was set down as cyclonic if the isobar on the 8 A.M. chart was concave to a region of low pressure, and as anticyclonic if the isobar was concave to a region of high pressure. The first classification was made according to the type of weather. It was thought possible that this second-order temperature effect might be a result of periodic variations in the relative frequency and effect of cyclonic and anticyclonic weather at different periods of the year. With the object of ascertaining whether this was the case,* the mean temperatures and frequencies of occurrence of cyclonic and anticyclonic weather, during each month of the year, were tabulated for the five years under observation. For the purpose of examining the results, curves of temperature were drawn whose ordinates are proportional, not to the absolute mean temperature for the month, but to the difference between the mean monthly temperature and the temperature which would be represented by the mean of the ordinates of the first-order curve during the month; so that the resulting curves show that part of the temperature variations which is represented in the harmonic analysis by a summation of all the curves of higher order than the first. Diagram 2, fig. 1 (p. 68), shows these curves of temperature for the cyclonic and anticyclonic days respectively. It will be seen that only during the three summer months, and to a slight extent during March, is the cyclonic weather cooler than the anticyclonic. But both the curves show the main characteristics of the second-order curve, viz., maxima in February and August, and minima in May and November. Moreover, the curve of difference of temperature between cyclonic and anticyclonic weather (fig. 2) shows three maxima in the year. Fig. 3 shows the differences in frequency of the two types of weather during each month, expressed as percentages of the whole number of days in the month; here again the curve is irregular, having several maxima which occur at irregular intervals, showing that the relative frequency of the two types of weather plays no part in causing the second-order effect. Finally, by multiplying the percentage difference of frequency of cyclonic and anticyclonic weather for each month, by the difference in temperature (excess of the cyclonic, in each case, being taken as positive, and *vice versâ*), a resulting curve (fig. 4) is obtained which gives the total effect of the type of weather on the atmospheric temperature. A glance at this curve will show that this effect is in no respect similar to the second-order effect. It is thus evident that the cyclonic or anticyclonic type of the weather plays no part in causing the second-order effect, which is nevertheless the only prominent periodic temperature variation which has a meteorological origin.

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* Mr. W. H. Dines, 'Quart Journ. Roy. Met. Soc.,' vol. 23, p. 237, has already given some reasons against regarding cold as definitely associated with anticyclonic weather in winter.

Diagram 2.

EFFECT OF TYPE (CYCLONIC OR ANTICYCLONIC) OF WEATHER ON TEMPERATURE. KEW 1876 TO 1880.

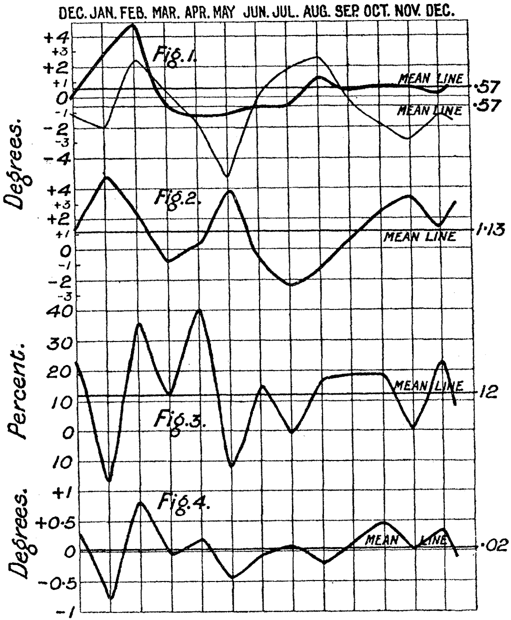


Fig. 1. Divergence from first order curve.
Thick during cyclonic weather.
Thin " anticyclonic "
Fig. 2. Cyclonic temperature - Anticyclonic.
Fig. 3. Frequency of cyclonic - Frequency of anticyclonic
Expressed as percentage of total number of days
Fig. 4. Effect of the type of weather on the divergence from first order curve.

The Effect of Wind-direction on Atmospheric Temperature during the Five Years 1876–1880.

A second classification was then made in which, while the types of weather were still distinguished, curves of the difference between first order curve values and mean daily temperature observed during the prevalence of barometric gradients for each of eight points of the compass, were separately drawn. Each of these curves showed certain characteristics which corresponded with some of those of the second-order curve; either the February maximum or the May minimum or some other characteristics were prominent, but no single one of the curves for the separate gradients showed a complete curve with all the characteristics of the second-order curve. It was, however, very remarkable that the curves for the same winds during different types of weather were closely parallel—a result which confirmed the previous observation that neither the mean difference in temperature between cyclonic and anticyclonic days, nor the relative frequency of their occurrence, could give rise to the second-order variation in atmospheric temperature, or indeed to any other simple periodic effect. It was therefore decided to abandon the separate classification of cyclonic and anticyclonic days.

Examination of the curves above described showed that the number of days on which any particular wind occurred during a ten-day interval in five successive years, was not sufficient to eliminate the effect of exceptional days from the mean value obtained. A further period, from 1880–1884, was therefore examined, and the curves were constructed from monthly means, instead of from ten-day means, for the nine years. Thus sufficient observations were obtained to give mean values which might be regarded as independent of single exceptional variations from the mean. The observations which were retained for the investigation were those relating to the days which had been previously classed as cyclonic or anticyclonic; the days which were not classified, on account of the want of any definite indication, were omitted. That this omission did not appreciably affect the results arrived at, may be inferred from the fact that one of the curves (Diagram 6, fig. 1, p. 75) could be obtained in two ways—first, by taking the temperature difference and frequency of wind for the included days, and, secondly, by taking the temperature difference from the actual means for all days. The results were quite identical in the two cases.

Effect of Wind-direction on Atmospheric Temperature during the Nine Years 1876–1884.

The effect of wind-direction on temperature was investigated by means of curves whose co-ordinates are respectively proportional to the period of the year and to the difference on any day between the observed mean daily temperature for the nine years and the temperature which would be represented on that day by the first order sine curve obtained by analysis of the twenty-five-year curve. The eight curves so obtained will be spoken of as the temperature curves for each wind; but it must be remembered that they do not represent observed temperatures, but differences between mean observed temperatures and temperatures given by the first-order curve at any given period of the year.

The term "for each wind" also requires some amplification. Owing to the marked effect of local geographical conditions at any station, the recorded direction of the wind does not necessarily give a very accurate estimate of the true quarter from which the station was obtaining its air supply, and it is of course the source of air supply which will affect the atmospheric temperature at any station. The days were, therefore, not classified according to the direction of the wind recorded as having been observed at Kew, but according to the direction of the gradient (high to low) at right angles to the isobars in the neighbourhood of the station, and a curve has been called the curve for the east wind when it really represents a curve for a southern gradient, and so on for other directions. It must be observed that the term "east" is not quite accurate, since the direction of air supply for a southern gradient will not be from due east, but from a little north of east. However, as we are only dealing with eight points of the compass, the direction of the wind when the gradient is to the south will be described with sufficient accuracy as an east wind.

In Diagram 3 the temperature curves for each wind are given. It will be seen that each curve tends to resemble in some important respects, and in kind, if not in degree, the second-order curve for the twenty-five-year means. For example, the east wind temperature curve has a minimum in the beginning of May, and maxima in August and February; but these are not equal minima and maxima, and the curve is obviously not simply harmonic. The north-east wind has a minimum in spring and autumn and a maximum in winter and summer, although the dates do not exactly correspond with those of the east wind. The curve for the north wind is irregular but has a distinct absolute maximum at the end of July. The curve for the north-west wind has its maxima in February and at the end of July, and minima in spring and autumn, and so on. Thus all the winds have curves whose characteristics suggest those of the second-order curve, although they are not identical with them, and the effect represented by the second-order curve is still apparent in the temperature curves for each separate direction of air supply, and consequently is to some extent independent of the quarter from which the air is supplied.

Diagram 3.

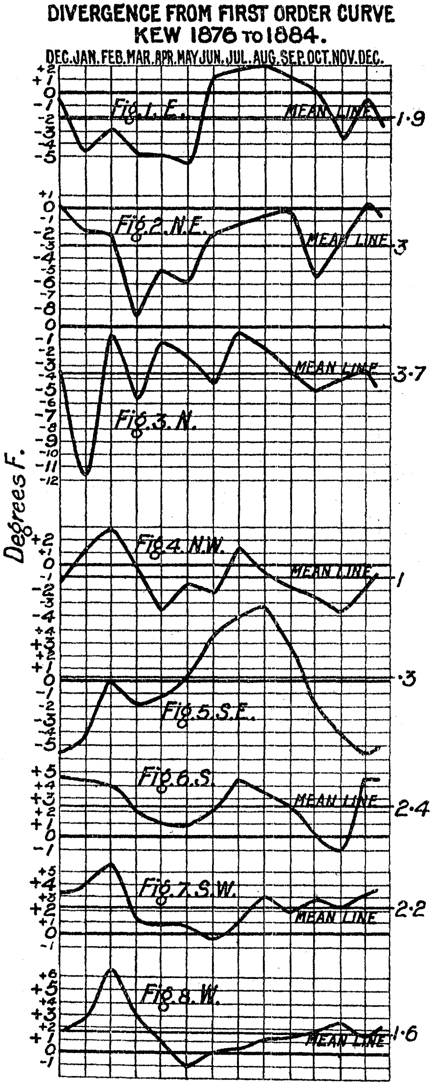


Fig. 1. During prevalence of E. winds.
" 2. " " " N.E. "
" 3. " " " N. "
" 4. " " " N.W. "
" 5. " " " S.E. "
" 6. " " " S. "
" 7. " " " S.W. "
" 8. " " " W. "

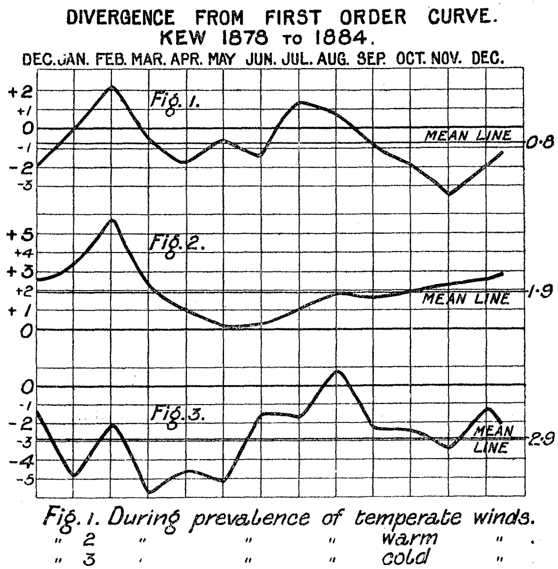
Warm, Cold, and Temperate Winds.

This has been shown more clearly by grouping the winds together according to their mean effect on atmospheric temperature. It was found that the mean difference between the observed temperatures and first-order curve temperatures for the whole year for—

1. E. wind (as defined above) was − 3°·1 F.
2. N.-E. " " " −4·0
3. N. " " " −3·5
4. S.-E. " " " −0·6
5. N.-W. " " " −0·7
6. W. " " " +1·9
7. S.-W. " " " +2·2
8. S. " " " +2·5

Seeing that the first three of these had a decided cooling effect, the next two a very slight cooling effect, and the last three a decided warming effect on the first order atmospheric temperature, these winds were studied in three groups, which we will call the "cold," "temperate," and "warm," and temperature curves were drawn for each of these groups (Diagram 4). Each of these three curves shows some resemblance with the second-order curve. There are very distinct winter maxima in February in all three. Both cold and warm winds

Diagram 4.



have minima in May and maxima late in July or early in August, and the temperate winds have a very distinct minimum in November. It is obvious, therefore, that the second-order effect is present in each separate wind and in separate groups of winds. Nevertheless we have eliminated, by separating the effect for each wind, part of the physical cause which gives rise to the second-order effect.

This is again shown in the curve which is obtained by compounding the eight temperature curves (Diagram 6, fig. 2, p. 75). This gives us a curve whose difference from the second-order curve* will represent that part of the effect which has been eliminated by separating the weather into these eight types: any effect on temperature which may arise from the relative frequency with which these various types occur will not have been taken into account. It will be seen that the characteristics of this curve (fig. 2, Diagram 6) approach those of the second-order curve far more closely than do those of the curves of individual winds. It has distinct maxima in February and August and minima in April and November, but the curve is not regular in its period although the period is approximately semi-annual. The February maximum follows a very sudden rise, and lies between two values for January and March which differ but very little from the minimum values in April and May; and moreover the minimum occurs somewhat earlier than the minimum of the second-order curve.

Relative Frequency of Occurrence of the Warm, Temperate, and Cold Winds.

We have thus separated a part of the physical cause of the second-order effect—a part which depends on the direction of air supply, *i.e.*, on the quarter from which the air is derived. The analysis may be pushed further by means of the three groups of winds which we mentioned above. Curves were drawn for each group of winds whose co-ordinates are respectively proportional to the period of the year and to the percentage of the total number of days (in each month for the nine years) on which the winds belonging to that group were observed to prevail (Diagram 5, p. 74). It will be seen that the cold group shows a very marked maximum percentage in May and a less marked one in November, and minima in July and at the end of December, all of which characteristics correspond approximately with the second-order curve. The curve for the warm winds shows an inverse correspondence, while the curve for the temperate winds, whose mean effect is small, but whose tendency is on the whole to lower the temperature, has certain points of correspondence with the curve for cold winds. It is obviously impossible to represent the total share of this effect of wind direction in bringing about the second-order effect by any method of direct composition of these curves, but the fact that each of the three groups gives a curve of frequency whose characteristics show this remarkable correspondence with those of the second-order curve, is sufficient evidence that the relative frequency of occurrence of winds from the various quarters plays some part in causing the second-order effect. What this part is is shown in Diagram 6. Fig. 1 gives the curve of mean temperature difference throughout the year, and fig. 2 gives the curve which is directly compounded of all the temperature curves for the various winds, so that the effect of relative frequency is eliminated; fig. 3 is obtained by subtracting the ordinates of fig. 2 from the corresponding ones of fig. 1, and may be taken as representing the effect upon temperature arising from the relative frequency of warm or cold winds. The main features of this curve are the winter maximum

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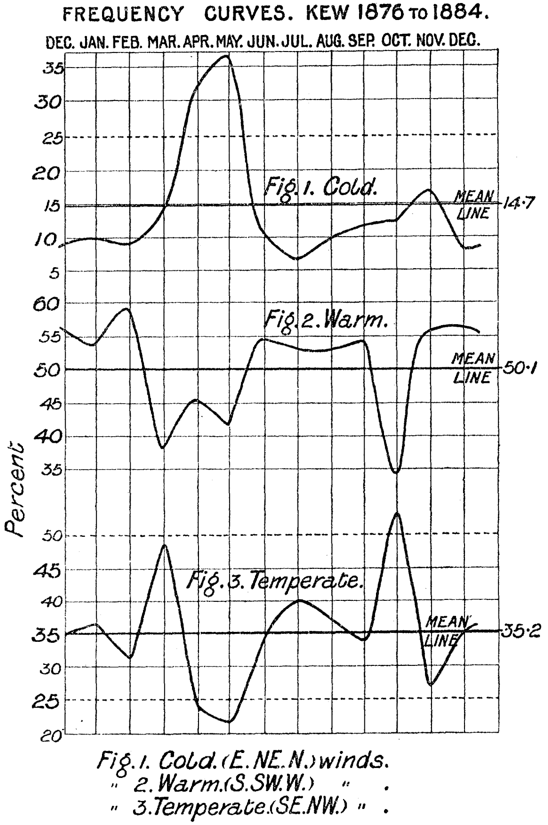
* Fig. 1, Diagram 6, represents the total residual temperature after subtracting the twenty-fifth year first-order component, and therefore shows the second component combined with the residual annual component for nine years, which has an amplitude of nearly ·5° F. and components of shorter period.

DIAGRAM 5.



and spring minimum, and a glance at figs. 1 and 2 will show that it is the frequency which converts the sudden warm effect in February, which is shown by the individual winds, into a gradual rise from autumn to winter and fall from winter to spring which are the features of the complete second-order curve. It will also be observed that the frequency effect has a maximum in July which brings back the maximum exhibited by the sum of the individual effects to its normal position. The October—November effect seems to be complete in the compounded curve, and, as was seen in Diagram 4, it has its origin chiefly in the curves of the south-east and north-west winds. Thus it appears that the second-order effect is to some extent independent of the direction of air supply, but that it is in part due to the relative frequency at different times of the year with which the air supply is derived from "hot," "cold," or "temperate" sources. At the periods of the maxima of the second-order curve the air supply of these islands is derived mainly from the warm sources, *i.e.*, south, south-west, and west, and at the periods of its minima, either from the coldest sources, which are the east, north-east, and north, or to a very predominant extent from the slightly cold sources, which are the south-east and north-west.

DIAGRAM 6.

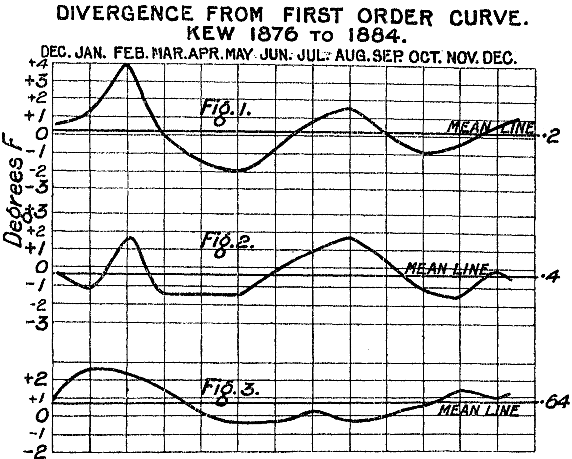


Fig. 1 Total effect.
" 2. Effect of compounding the curves for all winds without regard to the relative frequency of the various winds or groups of winds.
" 3. Difference between Fig. 1. and Fig. 2.

It is especially noteworthy that the cooling effect in May is due to the relative prevalence of winds from cold quarters (see Diagram 5, fig. 1), combined with the fact that "warm" winds and "cold" winds (Diagram 4, figs. 2 and 3) are relatively colder at that time than at other times of the year; whereas the cooling effect in October—November may be attributed to the prevalence of the winds we have called "temperate" (*i.e.*, N.W. and S.E. winds), which at that time of the year become especially cold.

The July maximum corresponds to exceptional warmth of the generally cold or temperate groups of winds (figs. 1 and 3 of Diagram 4), and the January maximum corresponds especially to the frequency of occurrence of warm winds.

Effect of the Length of Period Analysed on the Position and Amplitude of the Curve.

As has been stated above, these effects have all been studied for Kew, and reference has always been made to the analysis of the *twenty-five-year* mean curve of temperature for Kew. It will, however, be seen that a possibility of error is here introduced, since it cannot be assumed that the mean curve for the nine years on which our results have been mainly based would have the same harmonic coefficients as the curve for the twenty-five years. Analyses were therefore made of the curves of mean temperature for various periods of years at Kew (Table I). It will be seen that the first-order curves for the twenty-five years and nine years are practically identical, and the positions of the maxima of both the first- and second-order curves are also almost identical for the two periods of years. The third- and fourth-order curves are larger for the shorter period, but are still relatively small, so that the curves of difference from the twenty-five-year first-order curve, which we have been discussing above, fairly represent (as has been assumed) the nine-years second-order curve.

It may here be of interest to make a further study of Table I. It will be seen that not only the twenty-five and nine-year curves have been analysed, but also the curves for the five years and four years which made up the nine years, and again for four single individual years. Of these individual years, the year 1884 was chosen at random, the year 1873 on account of its extremely warm winter, and the year 1895 on account of its extremely cold and late winter. The results of the analysis for 1898—a year with exceptionally hot weather in August and September—have been added to the table. It shows a retarded first-order curve, with a second-order curve of mean amplitude and rather early maximum. It will be noticed that the coefficients of the first-order curve are practically the same in all the analyses, except those of the very abnormal years. A still more striking phenomenon is the persistence of the second-order effect not only in the twenty-five years, the nine years, the five years, and the four years, but also, and to an exaggerated extent, in the typical single year. The higher-order effects vary very much both in magnitude and in position, but the second-order effect is prominent in all the curves, and, except in the very exceptional years whose abnormality it shares, it has its maxima oscillating over the first ten days of February and August respectively. This oscillation again shows itself in the gradual decrease of the amplitude of the second-order effect as the number of years increases whose mean curve is analysed. Thus for the single year the amplitude is 3°·57 F.; for the five years it is 2°·06 F.; for the nine years 1°·95 F.; and for the twenty-five years, 1°·38 F. Thus Table I is in itself a sufficiently striking demonstration of the existence of a second-order meteorological effect which combines with the primary solar effect to give us our normal periodic variation of atmospheric temperature.

The gradual diminution of the amplitude of the second-order oscillation with the extension of the time over which the means are calculated, might perhaps be taken to indicate that if the means were sufficiently extended it would disappear altogether; and the fact that in hundred-year means for Vienna (which will be referred to later), the second-order amplitude is reduced to one degree, whereas the first-order amplitude is 19°·8 F., might be regarded as a further indication of the same fact. In the absence of data extending over the whole period it is, of course, impossible to form a definite opinion, but if the arrangement were so that the effect which appears in twenty-five-year means is obliterated in a hundred years, it would be very interesting to know how the second-order effect appeared in the other three groups of twenty-five years of which the hundred are made up. Some light might be thrown upon the matter by the analysis of all the component years of the original twenty-five, but this has not yet been carried out.

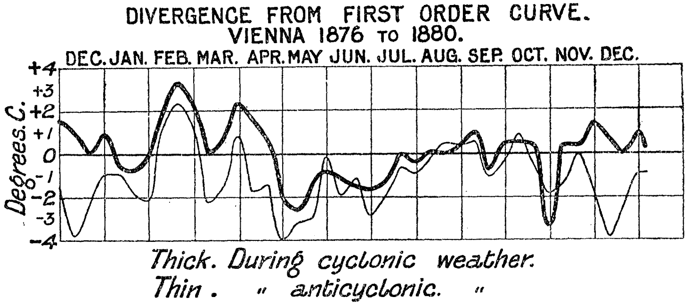
The fact that the maximum of the second order for Vienna comes on March 24 shows that the remaining effect there is different in character from that shown in the curves for the British stations.

Comparison of the Effect at Kew with that at the other Stations.

Reference has hitherto only been made to the Kew curves, since it is the Kew temperatures which have been studied in detail, but the analysis of the twenty-five-year mean temperature curves for Aberdeen, Valencia, and Falmouth are also given in Table I. The second-order curve is in each case about one-eighth of the first-order curve in amplitude, but the third-order curve is not always entirely negligible. At Kew its amplitude is only one-thirtieth of the second-order curve amplitude, and at Falmouth it is only one-seventh, so that in these cases the higher orders are entirely negligible. At Valencia and Aberdeen, however, the amplitude of the third-order curve approaches one-third of that of the second-order curve, and therefore becomes more important; but its amplitude amounts to only one-third of a degree, and the second-order effect thus remains the only one of any practical importance.

Mr. A. A. Rambaut* has harmonically analysed the curve of the monthly mean temperatures for a single year (1899) at Oxford with a similar result, and in this case, as in the analysis of the 1884 Kew temperatures, the second-order curve is comparatively very large. It will be seen that all the stations hitherto mentioned have been on or near the sea-coast, and indeed it may be said that all British stations are comparatively near to a sea-coast. It was therefore thought advisable to make an investigation of the temperatures at a Continental station, where the effects due to the proximity of the ocean would be eliminated. For this purpose Vienna was chosen. Dr. Hann, in a paper on the "Temperature of Vienna," based on observations for 100 years, gives the harmonic analysis of the curve of mean daily temperatures (Table I, Vienna). The amplitude of the second-order curve is only $\frac{1}{20}$th of that of the first-order curve, and that of the third-order curve is approximately of the same magnitude. Moreover, the weather at Vienna has been investigated for the years 1876–1880 in the same way as the weather at Kew, and curves of temperature difference from the first order curve value have been drawn for each wind and each type of weather. No definite periodic curves were obtained similar to those obtained for Kew, all the curves being different from one another, and in themselves irregular: the only universal characteristic was that the cyclonic and anticyclonic curves for the whole year (Diagram 7), and moreover for each wind, showed a remarkable parallelism, the cyclonic being almost always a little warmer

Diagram 7.



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* ‘Roy. Soc. Proc.,’ vol. 67, p. 221.

than the anticyclonic days. Thus there is no prominent effect at Vienna analogous to our second-order effect, but, as in these islands, whatever periodic meteorological temperature effects do exist, appear to be entirely independent of the relative frequency and mean temperature of cyclonic and anticyclonic weather. An analysis of the temperature curve for Agra, a typical Continental station in India, has also been made (Table I, Agra). Here there is a conspicuous second-order curve, but its position is entirely different from that of the corresponding curve for the British Islands, and its effect is to prolong the summer, whilst the second-order effect which has been discussed above shortens it. The two effects are thus in no way analogous, and this result, combined with the result of the Vienna investigation, makes it seem probable that the ocean plays a paramount part in the causation of the second-order temperature effect which we experience in these islands.

Analysis of Sea Temperatures.

With the object of further investigating this point, curves whose coördinates are respectively proportional to the fraction of the year, and to the mean temperature of the sea, based on three years' observations at Shetland, Scilly, and Yarmouth, have been analysed (Table II). The maxima and minima of these curves are all a little later in the year than those of the air-temperature curves, but the lag is approximately the same in all of them, and it is an obvious and striking fact that there is in the periodic variation of marine temperature an effect similar to the second-order effect observed in the periodic variations of atmospheric temperature. Whether this variation of the temperature of the water which surrounds these islands is the cause of the atmospheric second-order variation, or whether it is only another effect of the same fundamental cause, does not appear; but in view of the fact that the marked second-order effect is not seen at Continental stations, it would seem not unlikely that the ocean temperature is the immediate cause of our second order periodic temperature variation.

Analysis of Barometric Differences between London and Valencia and London and Aberdeen.

Table III gives the results of the analysis of the curves of thirty-year-mean difference of barometric pressure between London and Valencia, and London and Aberdeen, respectively. In each of these curves we again find the prominent second-order effect, although in the curve for London—Valencia it is somewhat earlier in its position than the temperature effect. Thus the magnitude of the barometric gradients for southerly and easterly winds shows a similar second order periodic variation to that which has been observed in the atmospheric temperature of these islands. In view of the close connection between barometric pressure and atmospheric temperature, it seems not unlikely that the one effect plays some part in the causation of the other.

The striking correspondence between the period of occurrence of the maximum of the second-order component of the gradient for westerly winds (London—Aberdeen) and the corresponding components for temperature, leads naturally to the suggestion that the periods of maximum and minimum of the second-order component of temperature are related to special barometric conditions. They may, and indeed must, be connected with some stage in the process of annual migration of the centres of high and low barometric areas, which is the result of the unequal distribution in longitude of the land areas in the northern hemisphere. A cursory survey of the mean monthly distribution of pressures in Dr. Buchan's volume of 'Bartholomew's Atlas,' shows that April is an exceptional month of transition, but up to the present we have not found any means of representing the successive stages of the transition in such a way as to enable a comparison to be made between them and the second-order curve of temperature.

The data used in this paper have been compiled in the Meteorological Office, or extracted from the various publications in the library of the office. The harmonic analysis has also been carried out there under the supervision of Mr. R. H. Curtis.

Summary.

The harmonic analysis of the curve of mean atmospheric temperature at stations in the British Isles shows that there is, compounded with the primary solar variation, a secondary half-yearly meteorological variation.

The effect of this variation is to moderate and lengthen the winter, and to intensify and shorten the summer.

The second-order curve which represents it, has maxima which oscillate, in different years, over the first ten days of February and August respectively, and minima which oscillate over the first ten days of May and November.

With some exceptions, the effect is generally apparent in a single year's observations, and, owing to its varying position, its curve appears to have a larger amplitude in the analysis of the temperature curve of a single year than in that of the mean curve of a number of years.

It is independent of the relative frequency of occurrence of cyclonic and anticyclonic weather, and of the relative temperature of the air during the prevalence of these different types of weather.

It is partly due to a periodic variation in the relative frequency of occurrence of the "cold," "warm," and "temperate" winds, but is

to some extent apparent during the prevalence of winds from all quarters.

It is not found, with maxima at the same epoch, in purely Continental stations, such as Vienna and Agra.

A similar effect is found in the temperature variation of the sea-water at stations surrounding these islands, and the atmospheric effect is probably connected with this.

A similar second order periodic effect is also found in the variation in the magnitude of the barometric gradient between London and Valencia and London and Aberdeen. It is probable that this periodic variation in pressure plays some part in causing the similar variation in temperature.

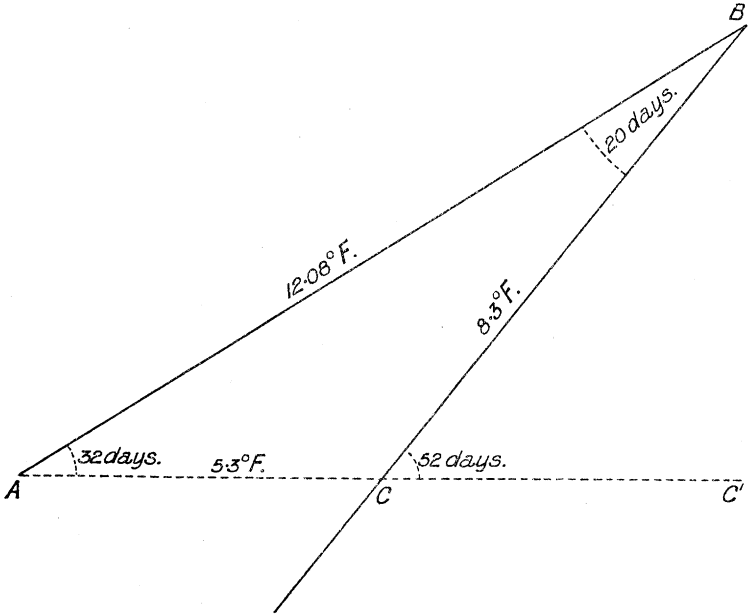
Note on the Effect of Sea Temperature upon the Seasonal Variation of Air Temperature.

It has been pointed out in referring to Table II. that the harmonic components of the first and second orders of the seasonal variations of the temperature of the sea in the neighbourhood of a coast station show a relative lag as compared with the corresponding components of the air temperature of the stations. On comparing Table II with Table I, it will readily be seen that the first-order curves for the coast stations show a definite lag as compared with the inland and Continental stations. Thus the earliest occurrence of a first-order maximum for a coast station in Table II is July 30, and in Table I July 28, while the relatively inland station, Kew, shows the first-order maximum on July 23, and Oxford (for a single year, however) on July 12. Vienna is earlier than Kew, July 18, and Agra still earlier, June 29. We may thus regard the sea as causing a considerable lag in the occurrence of the seasonal variations of temperature in the adjoining coast stations, while in the sea itself the lag is still greater.

Now we may regard the periodic variation of sea temperature as a cause affecting the air temperature of the stations, and, without knowing precisely the process connecting the cause and its effect, we may form some estimate of the relative magnitude in the following manner. Dealing only with the first-order components of the two related phenomena, we note that they are harmonic variations of the same period. We may assume that the effect of the periodic cause is itself simply harmonic and of the same period, and that the resultant first-order component for the air temperature is made up of a part which is independent of the sea temperature and a part which is dependent upon and caused by the sea temperature. We may thus assume the resultant first-order curve to be made up by compounding the two separate component curves.

The composition of harmonic curves of the same period is a geometrical process. Thus, if the length of AB, in fig. i, represents the amplitude of the resultant curve, AC, CB, the amplitudes of the two components, then, upon forming a triangle of the three, as in the figure, the angle BCC will represent the phase difference of the two components, BAC will represent the phase difference between the resultant and the first component, and ABC the phase difference between the resultant and second component.

Fig. i.



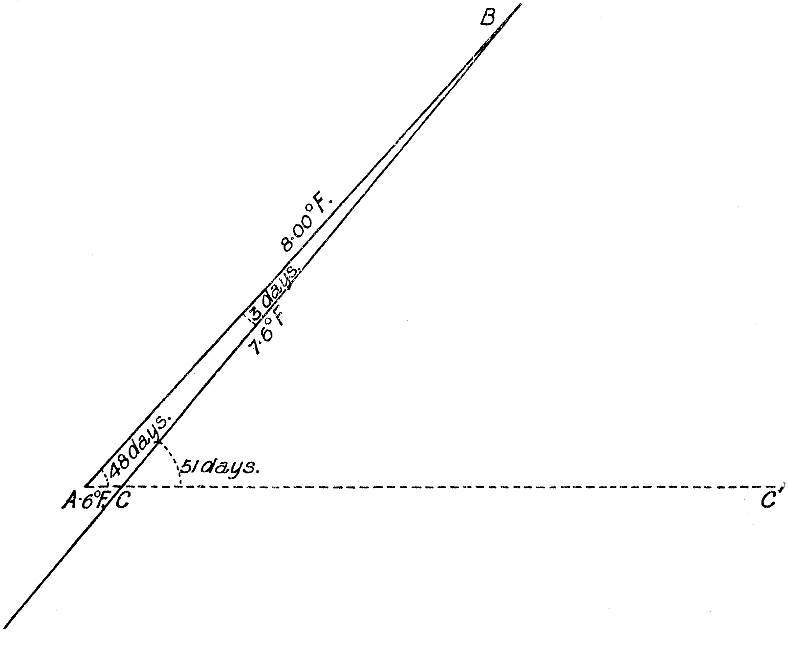
Applying these to the case under consideration, AC may be regarded as representing the temperature oscillation undisturbed by the effect of the sea temperature, CB the effect of the sea and AB the resultant effect or the actual temperature oscillation observed at the station. The angle ABC will represent the number of degrees of phase difference between the sea curve and the station curve, *i.e.*, practically, the number of days between the time of maximum on shore and on sea, and so on for the other angles. Of such a triangle for any station, the following elements are known: the resultant amplitude AB, the lag of the sea effect behind the land curve, *i.e.*, the angle ABC. The position of C is indeterminate because we do not know the actual magnitude of the sea effect BC, nor the magnitude or epoch of the undisturbed effect. But we know the extreme position of AC: it cannot correspond to a curve with an earlier maximum than June 21, when the planetary effect reaches its maximum. Drawing then the line AC corresponding to a maximum on June 21, we know that the sea effect cannot exceed BC in magnitude, and that the effect which is independent of the sea, cannot be less than AC.

Fig. i is a scale drawing representing this analysis of the temperature oscillation for Kew into two parts. It will be noticed in Table II that the sea temperature reaches its maximum at the Shetlands, at Scilly, and at Yarmouth on from August 10 to 13. Taking August 12 as a mean date, the sea effect reaches its maximum 20 days after the maximum of the first-order curve at Kew; the line BC is therefore ruled at 20° to AB. AC, being unknown, is dotted at an angle of 32°, corresponding to 32 days, the lag of the time of maximum at Kew behind the solstice (June 21). It follows from the measurements of the diagram that the sea effect at Kew cannot exceed 8°·3 F., and the original effect, apart from sea, cannot be less than 5°·3 F.

The mean amplitude of the sea variation is nearly 8° F., so that if the lag of the seasons at Kew is wholly due to the sea, the whole variation of temperature of the sea is superposed upon the initial variation. This would no doubt be an exaggeration, and the initial variation at Kew must be greater than the 5°·3 F. shown in the diagram.

A corresponding diagram drawn for Scilly from the air and sea temperatures there (fig. ii) represents nearly the whole temperature

Fig. ii.



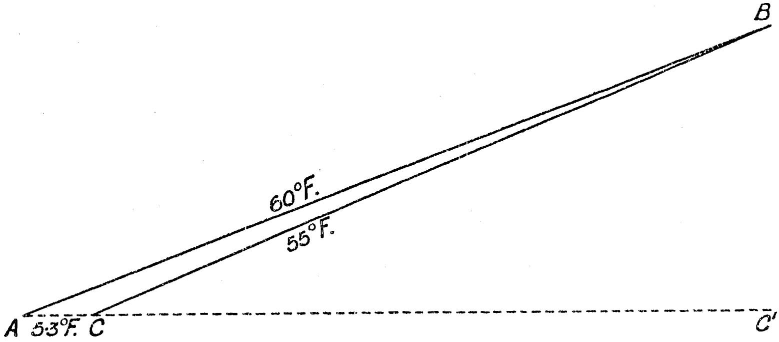
variation at Scilly as being due to the variation of sea temperature, but the sea temperatures are taken from means for a very short period, these being the only ones immediately available, and it would require a much more prolonged investigation of the sea data before a really trustworthy diagram could be drawn. When these are obtained for a number of stations it would not be difficult, by assuming the undisturbed climate to be the same for places in the same latitude, to conduct a satisfactory analysis of the elements of temperature of any place into its primary constituents. It is, however, apparent from this mode of resolution of the temperature oscillation into components that the more the components approach to coincidence of epoch the greater is the resultant effect. For example, if the sea temperature round the British Isles reached its maximum on June 21, the amplitude of temperature at Kew would be raised to 13°·6 F., and accordingly part of the intensity of a Continental climate may be attributed to the simultaneous heating of the large area over which the air for a Continental station passes.

There is another point of some interest which arises in connection with this subject, and that is, that all the successive stages of temperature change are delayed by the effect of the sea. Since both the first- and second-order components of the variation of sea temperature are of the same order of magnitude as those of the land curves, the effect of the sea is to delay the seasons, and we should on that account expect, not only the autumn and winter, but also the spring, to be later in a marine climate like that of Scilly or Falmouth than in an inland climate, and it would be interesting to ascertain how far such a conclusion is borne out by phenological observations. If this conclusion should be borne out, and there is at least some evidence in favour of it, one should seek an early spring, not on the coast, but inland, and on the other hand a late summer is more characteristic of the sea coast than of the inland country.

It may seem surprising that the effect of the sea upon the annual temperature oscillation of a place near it should be regarded as increasing the amplitude of the oscillation, whereas it is a matter of common knowledge that the effect of sea upon climate is to reduce the amplitude of the temperature oscillation as compared with that of a Continental station. But in fact the temperature range of any place depends upon the original range (which may be regarded as depending merely upon its latitude) and the increase of its range due to its surroundings. In the case of an ocean station the increase of range is small, because the temperature range of the ocean is itself small, and the epoch of its maximum is two months later than that of the planetary effect. At a Continental station the increase due to the surroundings is much larger and more nearly simultaneous with the original planetary effect.

The climatic conditions at a place like Kew, for example, which is not far from the sea, and which may be regarded (according to fig. 1) as having an original planetary temperature range of 10°·6 F., and a resultant range of 24° F., may be contrasted with those for such a station as Nertchinski-Zavod,* at about the same latitude, with a range of over 120° F. Its maximum is reached by the middle of July, consequently the composition of the original planetary range with the range due to the surrounding region is almost algebraical. On that understanding, and assuming that the planetary range is the same as that at Kew, we find that the influence of the surrounding land at Nertchinski-Zavod is to increase the range by 110° F., whereas the effect of the sea at Kew only adds 13°·6 F. to the range, *i.e.*, less than one-eighth of the land effect on the same latitude. The corresponding diagram would be as represented in fig. iii upon a scale of temperatures one-third of that of the other figures.

FIG. iii.



It is not, of course, a legitimate assumption that the planetary range corresponding to the latitude of Kew is accurately represented by 10°·6 F., which requires only to be compounded with the sea effect to produce the resultant oscillation. The resultant effect at Kew is probably resolvable into three components—one the original planetary effect with its maximum in June, a second due to the surrounding land with its maximum in July, and the third due to the sea with its maximum in August. The precise epoch of maximum of the land effect, which would identify the direction of its line on the diagram, and the actual magnitude of any one of the component effects, which would fix the position of the lines in the diagram, are not at present determinate, but their extreme limits are known.

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* Atlas Climatologique de l'Empire de Russie. St. Petersburg, 1900.